Recent Advances in Liquid Crystal THz Photonics

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INTRODUCTION

With dramatic advances of terahertz (THz) technology [1], high quality quasi-optic [2] components such as phase shifters, filters, and polarizers are in great demand lately. We have explored THz photonic elements with liquid crystal enabled functionalities recently [3]. In this report, we show our recent works on liquid crystal (LC) novel devices, including a Feussner-type terahertz polarizer [4], a Magnetically Tunable Liquid Crystal Phase Grating [5] and a liquid-crystal-based Solc filter [6].

Another work collaborating with Professors M. Hangyo and M. Tani of Osaka University about THz devices utilizing nonlinear optical effect in LC is on progress.

FEUSSNER-TYPE TERAHERTZ POLARIZER

As shown in Fig. 1, the polarizer employs a nematic liquid crystal (NLC) cell in the form of a rectangular parallelepiped made of fused silica. On its top (x-z plane), we cut a diagonal groove filled with LC (E7 form Merck). A pair of permanent magnets provides the magnetic field along y-direction (~ 0.2 T) to align LC molecules. The cell and magnets can be rotated synchronously along the z-axis. The rotating angle, ψ, is defined as the angle between the direction of magnetic field and the direction of x-axis.

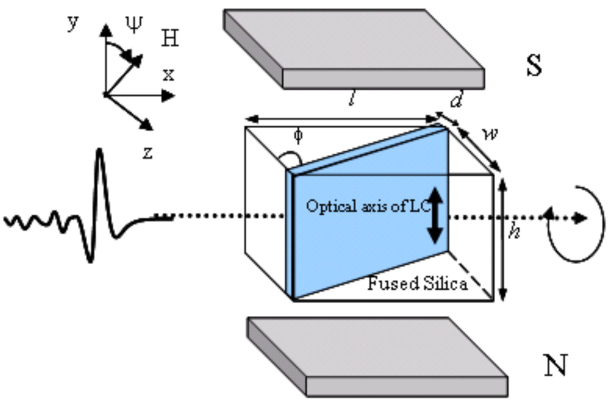

Fig. 1 Schematic drawing of the THz Feussner polarizer with a LC layer. The dimension of device, l×w×h, is 22.3 mm × 15 mm × 15 mm. The polarization direction of THz wave incident on the polarizer is along the y-axis.

We use the parameter, polarization factor, which is defined by

$$P = \frac{T_e(\omega) - T_o(\omega)}{T_e(\omega) + T_o(\omega)} \qquad (1)$$

to quantify the performance the polarizer. In Eq. (1), $T_e(\omega)$ and $T_o(\omega)$ are power spectral transmittance when the incident electric vector of THz wave is parallel and perpendicular to the optical axis of LC molecules, respectively.

In Fig. 2, we show the experimental data and theoretical predictions of polarization factors of three LC THz polarizers. For the polarizer with 0.75 mm-thick LC layer, $P > 0.95$ when f > 0.44 THz. It is, however, not an effective one in the lower sub-THz frequency ranges as the LC layer thickness is comparable or shorter than that of the wavelengths. The polarizer with 1.95 mm-thick LC layer, on the other hand, exhibits the best P value, which is greater than 0.99 for $f > 0.20$ THz.

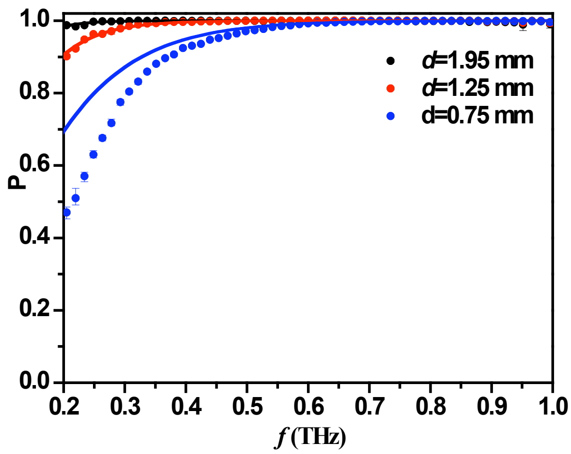

Fig. 2 Polarization factors of THz LC polarizers are plotted as a function of frequency. The black, red and blue colors represent the polarizer with 1.95 mm, 1.25 mm and 0.75 mm-thick LC layer, respectively. The circles and curves are the experimental data and theoretically predicted polarization factors.

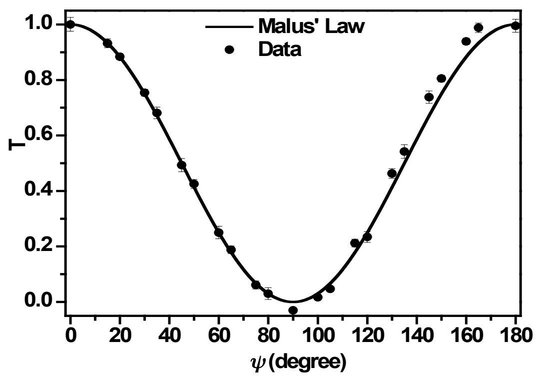

Fig. 3 Normalized peak transmission of the THz wave propagated through the THz LC polarizer as a function of the rotation angle, ψ. Solid line is the theoretical curve according to Malus' law

The peak values of THz field transmitted through the polarizer rotated at different angles ψ with respect to the incident polarization, normalized to the peak value of THz field at $\psi = 0°$ are plotted in the inset of Fig. 3. The agreement with the theoretical curve according to Malus' law is excellent.

MAGNETICALLY TUNABLE LIQUID CRYSTAL PHASE GRATING

We demonstrated for the first time a tunable LC phase grating in the THz frequency range. The diffraction effect of the grating is magnetically switchable by changing the effective refractive index of the NLC.

Figure 4 illustrated schematically structure of the LC phase grating, which was designed such that the first-order diffraction efficiency would be highest around 0.3 – 0.5 THz. Parallel grooves having a period of 2.0 mm, a width of 1.0 mm, and a groove-depth of 2.5 mm were fabricated on a 10.0 mm thick fused silica substrate. The grooves were filled with the NLC, E7 (Merck) and sealed with a sheet of Teflon. The dimensions of the grating were designed to have the maximum range of adjustment for the beam splitting ratio at 0.3 THz.

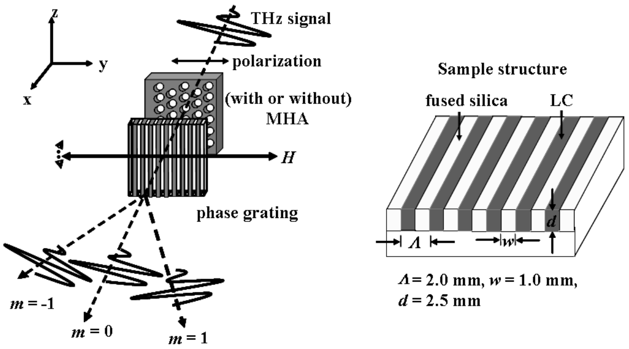

Fig. 4. (a) Experimental setup; H: magnetic field, MHA: metallic hole array used as narrow band filter. (b) Construction of the LC phase grating; dimensions were shown.

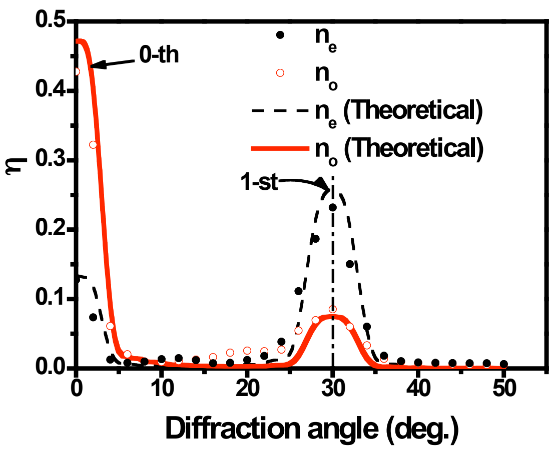

Fig. 5. Diffraction profiles of the LC phase grating for the 0.3 THz-beam. The grating operated as a variable beam splitter for the zeroth and the first-order diffracted beam.

Figure 5 illustrated the diffracted intensity profiles of the 0.3 THz-beam polarized in the y-direction. The measured diffraction efficiencies for 0^{th} and 1^{st} orders were 0.43 and 0.08 for o-ray, 0.13 and 0.23 for e-ray, respectively. These were also in good agreement with the theoretical estimate, taking into account of the finite dimension of the grating and acceptance angle of the bolometer.

A diffraction maximum was detected at θ = 30°, which corresponds to the first-order diffracted beam that was predicted by classical diffraction theory. As mentioned in the preceding paragraph, when the phase difference Δϕ was close to 2π, most of the THz signal propagated in the direction of the zeroth-order diffraction if the refraction index of E7 was n_o. Experimentally, we found the diffraction efficiencies were 0.43 and 0.08 for the zeroth and first-order diffracted beams, respectively. When the phase difference Δϕ was close to π, the refractive index of E7 was n_e and the THz wave mostly propagated as the first-order diffracted beam. The diffraction efficiencies were 0.13 and 0.23 for the zeroth and first-order diffracted beams, respectively. The grating thus served as a variable beam splitter. Rotating the magnetic field direction enabled the beam splitting ratio between the zeroth and first-order diffracted beams to be tuned from 4:1 to 1:2.

LIQUID-CRYSTAL-BASED SOLC FILTER

The LC-based Solc filter has two folded retarders. Due to limitation of the experimental setup, we used parallel polarizers (Fig.6) The tunable retarders (TR) are homeotropically aligned NLC (E7 by Merck) cells at the center of the rotatable magnet. TRs are oriented at 22.5° and - 22.5° with respect to the polarization of input light used to achieve the desired variable phase retardation, ΔΓ.

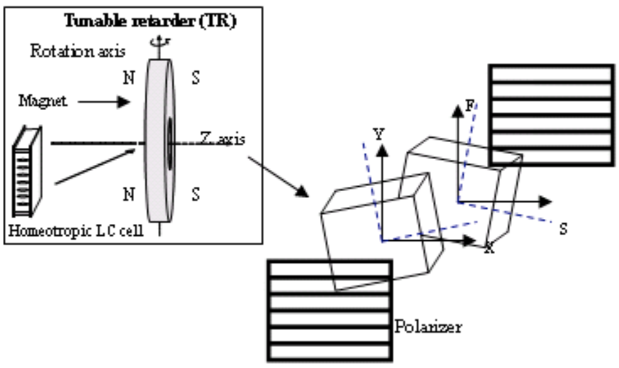

Fig.6. Schematic diagram of the LC-based tunable THz Solc filter. The inset shows a magnetically tunable LC THz phase shifter.

Figure 7 shows the spectral transmittance of the filter, converted by taking into account the parallel-polarization configuration, with the rotation angle from 40° to 90°, normalized to the maximum of transmittance. The transmitted peak frequency and the band width of the filter at angle 40° are 0.519 THz and ~0.409 THz, respectively; the transmitted peak frequency and the band width of the filter at angle 90° are 0.205 THz and ~0.118 THz, respectively. The theoretical curves (solid curves) are also shown, which is in good agreement with the experimental data.

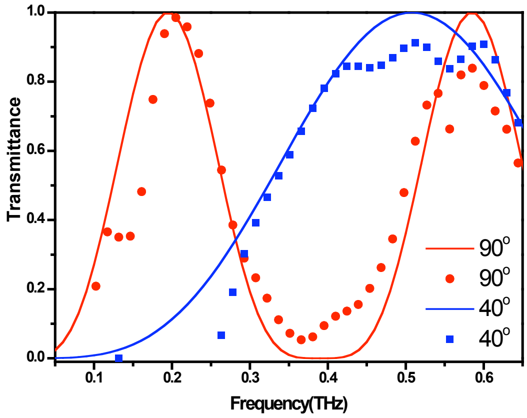

Fig. 7 An example of the transmitted spectrum of the broadband THz pulse which is tuned using the LC THz Solc filter. The circles and squares are experimental data and the solid lines are theoretical prediction.

The peak transmitted frequencies of the filter decreases with increasing rotating θ (see fig. 8). The tuning range of the filter is from 0.205 to 0.793 THz or a fractional tuning range of ~ 117.8%. The insertion loss of the device is around 5 dB. It is tentatively attributed to the scattering of THz wave by the LC molecules in the thick cells used.

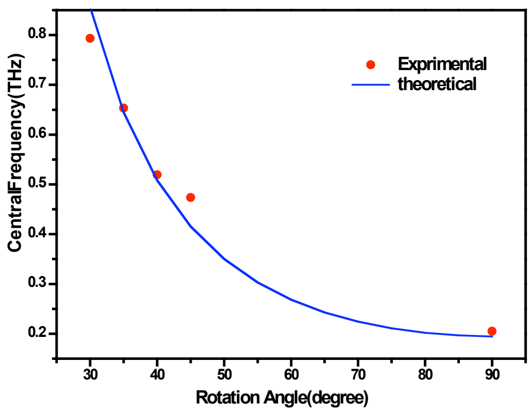

Fig. 8 . The central transmitted frequencies of the filter versus rotation angle θ. The circles are experimental data. The curve is theoretical line

SUMMARY

We demonstrated several promising THz photonic elements with liquid crystal enabled functionalities. These devices all operate at room temperature and thus are easy to use. With advances in liquid crystal materials with higher birefringence and even better transparency, we expect liquid crystal devices to play an important role in the THz frequency range as well as these have been successful in the visible and near infrared.

ACKNOWLEGEMENT(S)

Ru-Pin Pan would like to thank Institute of Laser Engineering, Osaka University for its hospitality. This work was also supported in part by the PPAEU-II and grant NSC 95-2221-E-009-249 from the National Science Council as well as the ATU program of the Ministry of Education of the Republic of China.

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